

Latest on the muon $g-2$ from experiment

*Graziano Venanzoni*¹

Laboratori Nazionali di Frascati dell' INFN, Frascati, Italy

graziano.venanzoni@lnf.infn.it

Abstract We review the latest experimental achievements on the hadronic cross section measurements at low energy which are of fundamental importance for a precise evaluation of the hadronic contribution to the $g-2$ of the muon. We also discuss the new proposed muon $g-2$ experiments, with particular emphasis on E989 at Fermilab which plans to improve the experimental uncertainty by a factor of 4 with respect to the previous E821 experiment at BNL.

1 The muon anomaly as a precision test of the Standard Model

The muon anomaly $a_\mu = (g-2)/2$ is a low-energy observable, which can be both measured and computed to high precision [1]. Therefore it provides an important test of the Standard Model (SM) and allows a sensitive search for new physics [2]. Since the first precision measurement of a_μ from the E821 experiment at BNL in 2001 [3], there has been a discrepancy between its experimental value and the SM prediction. This discrepancy has been slowly growing due to recent impressive theory and experiment achievements. Figure 1 (from Ref. [4]) shows an up-to-date comparison of the SM predictions by different groups and the BNL measurement for a_μ . Evaluations of different groups are in very good agreement, showing a persisting 3σ discrepancy (as, for example, $26.1 \pm 8.0 \times 10^{-10}$ [4]). It should be noted that both theoretical and experimental uncertainties have been reduced by more than a factor of two in the last ten years².

The accuracy of the theoretical prediction (δa_μ^{SM} , between 5 and 6×10^{-10}) is limited by the strong interaction effects which cannot be computed perturbatively at low energies. Table 1 shows their contribution to the error for three recent estimates [6, 7, 4]³. The leading-order hadronic vacuum polarization contribution, a_μ^{HLO} , gives the main uncertainty (between 4 and 5×10^{-10}). It can be related by dispersion integral to the measured hadronic cross sections, and it is known with a fractional accuracy of 0.7%, i.e. to about 0.4 ppm. The $O(\alpha^3)$ hadronic

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²In 2001 this discrepancy was $(23.1 \pm 16.9) \times 10^{-10}$ [5].

³Ref. [6] uses a more conservative error analysis.

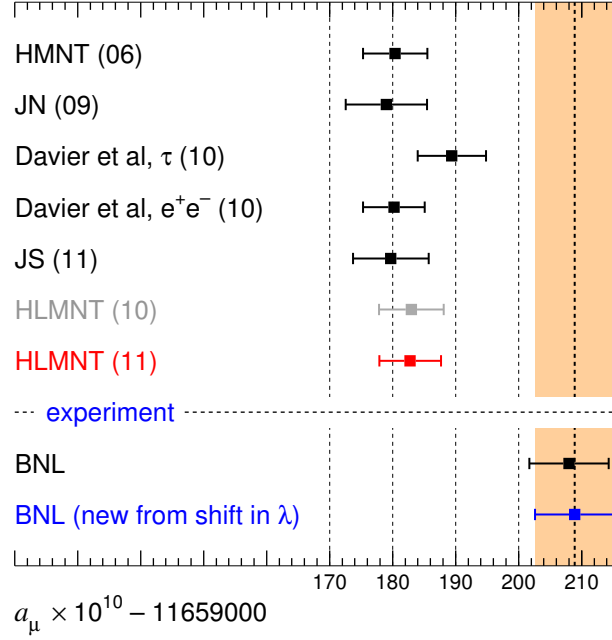


Figure 1: Standard Model predictions of a_μ by several groups compared to the measurement from BNL (from Ref. [4]).

light-by-light contribution, a_μ^{HLbL} , is the second dominant error in the theoretical evaluation. It cannot at present be determined from data, and relies on specific models. Although its value is almost one order of magnitude smaller than a_μ^{HLO} , it is much worse known (with a fractional error of the order of 30%) and therefore it still gives a significant contribution to δa_μ^{SM} (between 2.5 and 4×10^{-10}). From the experimental side, the error achieved by the BNL E821 experiment is $\delta a_\mu^{\text{EXP}} = 6.3 \times 10^{-10}$ (0.54 ppm) [8]. This impressive result is still limited by the statistical error, and experiments to measure the muon $g-2$ with a fourfold improvement in accuracy have been approved at Fermilab [9] and J-PARC [10].

2 Recent progress on the hadronic contribution to a_μ

Differently from the QED and Electroweak contributions to a_μ , which can be calculated using perturbation theory, and therefore are well under control, the hadronic ones (LO VP and HLbL) cannot be computed reliably using perturbative QCD. The lowest order hadronic contribution a_μ^{HLO} can be computed from hadronic e^+e^- annihilation data via a dispersion relation, and

Error	[6]	[7]	[4]	prospect
δa_μ^{SM}	6.5	4.9	4.9	3.5
$\delta a_\mu^{\text{HLO}}$	5.3	4.2	4.3	2.6
$\delta a_\mu^{\text{HLbL}}$	3.9	2.6	2.6	2.5
$\delta(a_\mu^{\text{SM}} - a_\mu^{\text{EXP}})$	8.8	8.0	8.0	4.0

Table 1: Estimated uncertainties δa_μ in units of 10^{-10} according to Refs. [6, 7, 4] and (last column) prospects in case of improved precision in the e^+e^- hadronic cross section measurement (the prospect on $\delta a_\mu^{\text{HLbL}}$ is an *educated guess*). Last row: Uncertainty on Δa_μ assuming the present experimental error of 6.3 from BNL-E821 [8] (first two columns) and of 1.6 (last column) as planned by the future ($g-2$) experiments [9, 10].

therefore its uncertainty strongly depends on the accuracy of the experimental data. For the hadronic Light-by-Light contribution a_μ^{HLbL} there is no direct connection with data and therefore only model-dependent estimates exist. As the hadronic sector dominates the uncertainty on the theoretical prediction a_μ^{SM} , considerable effort has been put on it by experimental and theoretical groups, reaching the following main results:

- A precise determination of the hadronic cross sections at the e^+e^- colliders (VEPP-2M, DAΦNE, BEPC, PEP-II and KEKB) which allowed a determination of a_μ^{HLO} with a fractional error below 1%. These efforts led to the development of dedicated high precision theoretical tools, like the inclusion of high-order Radiative Corrections (RC) and the non-perturbative hadronic contribution to the running of α (i.e. the vacuum polarisation, VP) in Monte Carlo (MC) programs used for the analysis of the data [11];
- Use of *Initial State Radiation* (ISR) [12, 13, 14] which opened a new way to precisely obtain the electron-positron annihilation cross sections into hadrons at particle factories operating at fixed beam-energies [15, 16];
- A dedicate effort on the evaluation of the Hadronic Light-by-Light contribution, where two different groups [17, 6] found agreement on the size of the contribution (with slightly different errors), and therefore strengthening our confidence in the reliability of these estimates;
- An impressive progress on QCD calculation on the lattice, where an accuracy better than 3% was reached on the two-flavor QCD correction to a_μ^{HLO} [18];
- Better agreement between the e^+e^- and the τ based evaluation of a_μ^{HLO} , thanks to improved isospin corrections [7]. These two sets of data are eventually in agreement (with τ

data moving towards e^+e^- data) after including vector meson and $\rho - \gamma$ mixing [19, 20].

3 σ_{had} measurements at low energy

In the last few years, big efforts on e^+e^- data in the energy range below a few GeV led to a substantial reduction in the hadronic uncertainty on a_μ^{HLO} . Figure 2 shows an up-to-date compilation of these data. The main improvements have been achieved in the region below

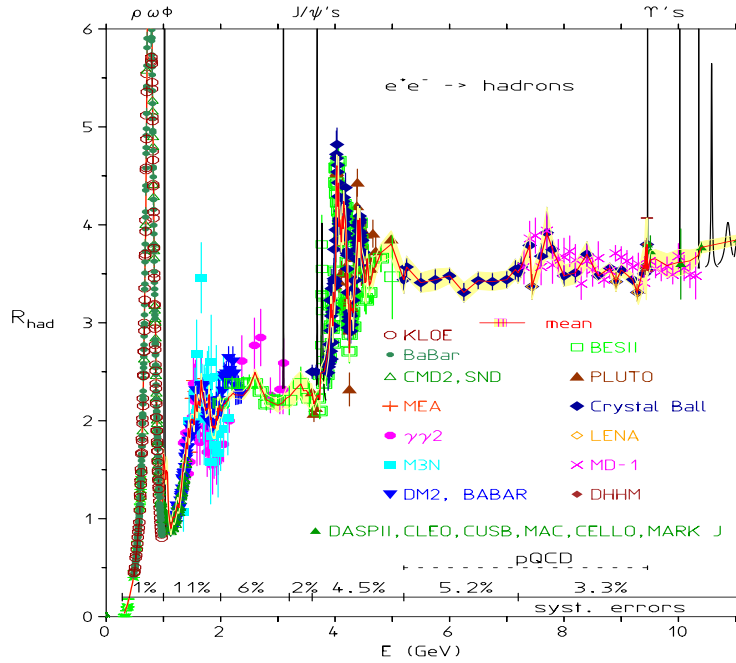


Figure 2: An updated compilation of R measurements. In the bottom line the overall uncertainties of the different regions are reported (*courtesy of Fred Jegerlehner*).

5 GeV: between 2 and 5 GeV (where the data are now closer to the prediction of pQCD), the BESII collaboration reduced the error to $\sim 7\%$ [21] (before it was $\sim 15\%$); between 1 and 4.5 GeV BaBar measured various final states with more than two hadrons with a systematic accuracy between 3% and 15%, as shown in Tab. 3; below 1 GeV, the CMD-2 [22, 23, 24] and SND [25] collaborations at Novosibirsk, KLOE [26, 27, 28] at Frascati and BaBar [29] at Stanford measured the pion form factor in the energy range around the ρ peak with a systematic error of 0.8%, 1.3%, 0.9%, and 0.5%, respectively.

Process	Systematic accuracy
$\pi^+\pi^-\pi^0$	(6-8)%
$2\pi^+2\pi^-$	(3-8)%
$2\pi 2\pi^0$	(8-14)%
$2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-)\eta$	(7-10)%
$3\pi^+3\pi^-, 2\pi^+2\pi^-2\pi^0$	(6-11)%
$KK\pi, KK\eta$	(5-6)%
$K^+K^-\pi\pi$	(8-11)%
$K^+K^-\pi^+\pi^-\pi^0, K^+K^-\pi^+\pi^-\eta$	(5-10)%
$2(K^+K^-)$	(9-13)%

Table 2: Systematic accuracy on more than two hadrons processes studied by BaBar in the energy range $1 < \sqrt{s} < 4.5$ GeV using ISR.

The CMD-2 and SND collaborations at Novosibirsk and BESII in Beijing were performing the hadronic cross section measurements in a traditional way, i.e., by varying the e^+e^- beam energies. KLOE, BaBar, and more recently Belle used ISR (also called *radiative return*) as reviewed in Refs. [11, 15, 16]. Figure 2 shows that, despite the recent progress, the region between 1 and 2 GeV is still poorly known, with a fractional accuracy of $\sim 6\%$. Since about 50% of the error squared, $\delta^2 a_\mu^{\text{HLO}}$ comes from this region (see Fig. 3), it is evident how desirable an improvement on the hadronic cross section of this region is.

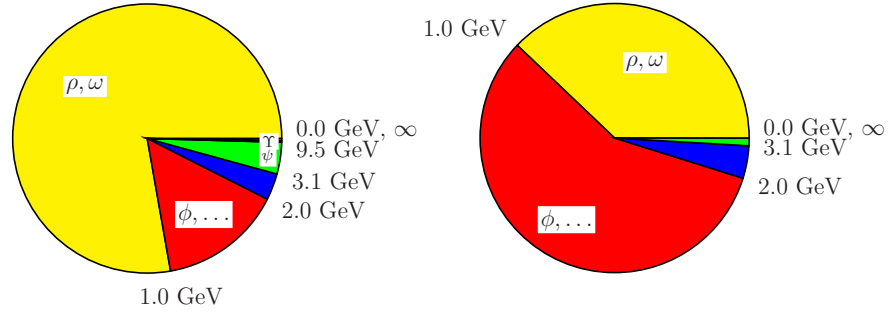


Figure 3: The distribution of contributions (left) and errors (right) in % for a_μ^{HLO} from different energy regions. The error of a contribution i shown is $\delta_{i\text{tot}}^2 / \sum_i \delta_{i\text{tot}}^2$ in %. The total error combines statistical and systematic errors in quadrature (from Ref. [6]).

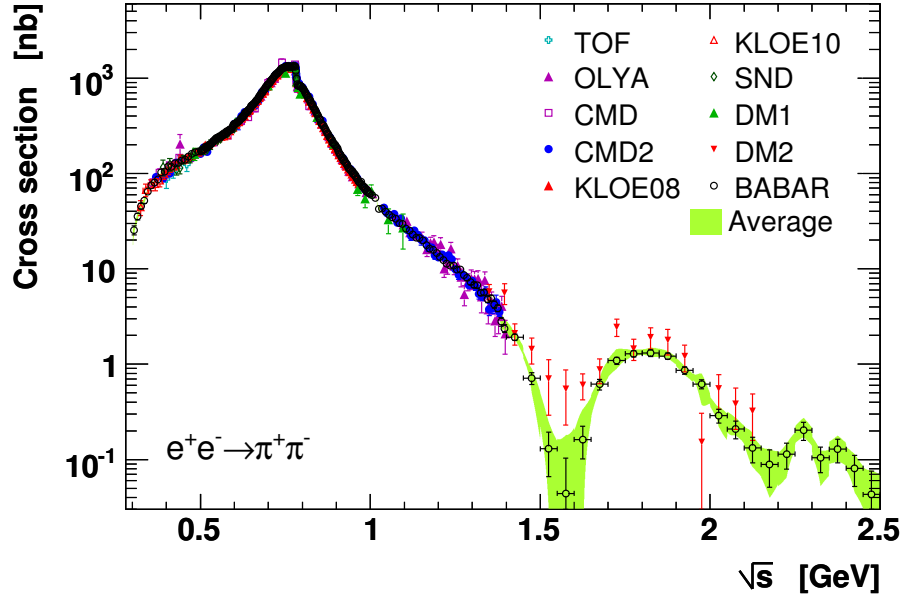


Figure 4: Cross section of $e^+e^- \rightarrow \pi^+\pi^-$ as measured by different experiments (from Ref. [7]).

3.1 Measurement of $\sigma_{\pi\pi}$ below 1 GeV

The region below 1 GeV is dominated by the two-pion channel which accounts for 70% of the contribution to a_μ^{HLO} , and for 40% to the total squared error of a_μ (see Fig. 3). Therefore due to its particular importance, it has been studied by different experiments as shown in Fig. 4. CMD-2 and SND have performed an energy scan at the e^+e^- collider VEPP-2M ($\sqrt{s} \in [0.4\text{--}1.4]$ GeV) with $\sim 10^6$ and $\sim 4.5 \times 10^6$ events respectively, and systematic fractional errors from 0.6% to 4% in the cross sections, depending on \sqrt{s} . The pion form factor has also been measured by KLOE and more recently by BaBar, both using ISR. KLOE collected more than 3.1 million events, corresponding to an integrated luminosity of 240 pb^{-1} , leading to a relative error of 0.9% in the energy region $[0.6\text{--}0.97]$ GeV dominated by systematics. BaBar has performed a $\pi^+\pi^-(\gamma)$ cross section measurement based on half a million selected events. The pion form factor is obtained by the ratio $\pi^+\pi^-(\gamma)$ to $\mu^+\mu^-(\gamma)$ which allows a systematic error of 0.5% in the ρ region increasing to 1% outside. The threshold region $[2m_\pi - 0.5 \text{ GeV}]$ provides 13% of the total $\pi^+\pi^-$ contribution to the muon anomaly: $a_\mu^{\text{HLO}} [2m_\pi - 0.5 \text{ GeV}] = (58.0 \pm 2.1) \times 10^{-10}$. To overcome the lack of precision data at threshold energies, the pion form factor is extracted from a parameterization based on ChPT, constrained by spacelike data [30]. The most effective way to measure the cross section near the threshold in the timelike region is provided by ISR events, where the emission of an energetic photon allows to study the two pions at rest. BaBar has achieved an error between 0.8 and 1.4% in this region, while KLOE has achieved a larger error (up to 7%) dominated by the point-like model uncertainty for FSR.

There is a fair agreement between the four experiments in the region below 1 GeV, with a discrepancy of about 2-3% between KLOE (lowest cross section) and BaBar (highest cross section) at the ρ peak, and CMD2 and SND somehow in the middle. Although small, this difference is larger than the claimed systematic error and can be a limitation for further improvements of a_μ^{SM} . As BaBar and KLOE (published) data use a different normalization (to muon pair and to Bhabha events, respectively) it may be that part of this difference can come from the normalization procedure itself. In order to check this possibility, the KLOE experiment has recently presented a new *preliminary* measurement of the pion form factor derived from the bin-by-bin $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio [31] as done in BaBar. As can be shown in Fig. 5, good agreement is found

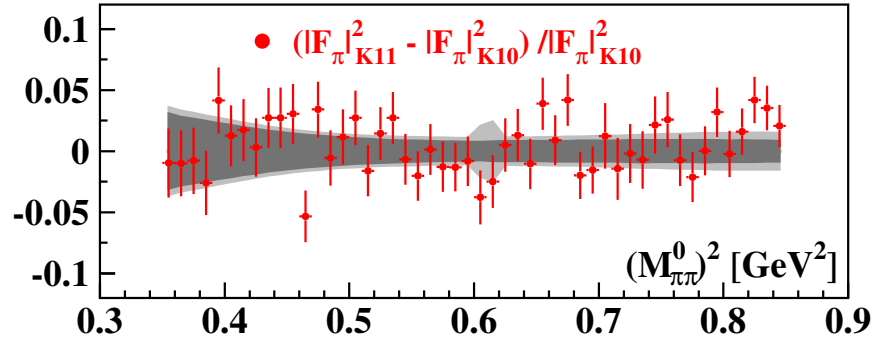


Figure 5: Fractional difference between the published KLOE measurement normalized to Bhabha events [26] and the new *preliminary* one derived from the bin-by-bin $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio.

between the two spectra, which excludes possible problems in the normalization procedure used in KLOE.

3.2 Measurement of σ_{had} above 1 GeV

The region [1–2.5] GeV, with an uncertainty on σ_{had} between 6 and 10%, is the most poorly known, and contributes about 55% of the uncertainty on a_μ^{HLO} (see Fig. 3). In this region BaBar using ISR has published results on e^+e^- into three, four, five and six hadrons, with a general improvement with respect to the much less precise measurements from M3N, DM1 and DM2. For several channels, BaBar measured lower cross sections with respect to older experiments, resulting in a reduced contribution from this energy region to a_μ^{HLO} . Recently CMD-3 and SND experiments at the upgraded VEPP-2000 collider in Novosibirsk have presented new measurements on multihadron channels [32]. With about 20 pb^{-1} of collected data, they have achieved

a statistical error comparable to ISR data from B-factories. VEPP-2000 plans to collect an integrated luminosity of 1 fb^{-1} , which would allow a significant improvement for many channels in the region below 2 GeV.

With a specific luminosity of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, DAΦNE upgraded in energy, could perform a scan in the region from 1 to 2.5 GeV, collecting an integrated luminosity of 20 pb^{-1} per point corresponding to few days of data taking for each energy bin [33]. By assuming an energy step of 25 MeV, the whole region would be scanned in one year of data taking. The statistical yield would be one order of magnitude higher than what would have been achieved with 1 ab^{-1} at BaBar, and better than what is to be expected at BESIII with 10 fb^{-1} at 3 GeV.

Finally, prospects of reaching an integrated luminosity by a factor of 30-100 exceeding that of the present machines appear at Super B-Factories. Such machines will improve accuracy for many processes whose studies are now statistically limited.

4 Measuring a_μ

The muon anomaly a_μ has been measured with better and better accuracy during the last 50 years. The E821 experiment at Brookhaven has reached an impressive 14-fold improvement in precision with respect to the pioneering measurements performed at CERN. Two new experiments with a goal of fourfold improvement in accuracy are underway: the approved E989 at Fermilab [9], and the J-PARC proposal [10] that has recently received stage-one approval. E989 is based on the well known magic-momentum concept and uses the BNL storage ring as a key element. The proposal at J-PARC uses a new approach with ultra-slow muons at off-magic momentum. We will now discuss how the measurement of a_μ is done, describing the E821 experiment, and its upgrade E989.

The measurement of a_μ uses the spin precession resulting from the torque experienced by the magnetic moment when placed in a magnetic field. An ensemble of polarized muons is introduced into a magnetic field, where they are stored for the measurement period. The rate at which the spin rotates relative to the momentum vector is given by the difference in frequency between the spin precession and cyclotron frequencies. Because electric quadrupoles are used to provide vertical focusing in the storage ring, their electric field is seen in the muon rest frame as a moving magnetic field that can affect the spin precession frequency. In the presence of both \vec{E} and \vec{B} fields, and in the case that $\vec{\beta}$ is perpendicular to both, the anomalous precession frequency (*i.e.* the frequency at which the muons spin advances relative to its momentum) is

$$\begin{aligned} \vec{\omega}_a &= \omega_S - \omega_C \\ &= -\frac{q}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] \end{aligned} \quad (1)$$

The experimentally measured numbers are the muon spin frequency ω_a and the magnetic field,

which is measured with proton NMR, calibrated to the Larmor precession frequency, ω_p , of a free proton. The anomaly is related to these two frequencies by

$$a_\mu = \frac{\tilde{\omega}_a/\omega_p}{\lambda - \tilde{\omega}_a/\omega_p} = \frac{R}{\lambda - R}, \quad (2)$$

where $\lambda = \mu_\mu/\mu_p = 3.183345137(85)$ (determined experimentally from the hyperfine structure of muonium), and $R = \tilde{\omega}_a/\omega_p$. The tilde over ω_a means that it has been corrected for the electric-field and pitch ($\vec{\beta} \cdot \vec{B} \neq 0$) corrections [3]. The magnetic field in Eq. 1 is an average that can be expressed as an integral of the product of the muon distribution times the magnetic field distribution over the storage region. Since the moments of the muon distribution couple to the respective multipoles of the magnetic field, either one needs an exceedingly uniform magnetic field, or exceptionally good information on the muon orbits in the storage ring, to determine the $\langle B_\mu \rangle$ distribution to sub-ppm precision. This was possible in E821 where the uncertainty on the magnetic field averaged over the muon distribution was 30 ppb (parts per billion). The coefficient of the $\vec{\beta} \times \vec{E}$ term in Eq. 1 vanishes at the “magic” momentum of 3.094 GeV/c; where $\gamma = 29.3$. Thus a_μ can be determined by a precision measurement of ω_a and B. At this magic momentum, the electric field is used only for muon storage and the magnetic field alone determines the precession frequency. The finite spread in beam momentum and vertical betatron oscillations introduce small (sub ppm) corrections to the precession frequency. These are the only corrections made to the measurement.

The experiment consists of repeated fills of the storage ring, each time introducing an ensemble of muons into a magnetic storage ring, and then measuring the two frequencies ω_a and ω_p . The muon lifetime at the magic momentum is 64.4 μ s, and the data collection period is typically 700 μ s. The $g-2$ precession period is 4.37 μ s, and the cyclotron period ω_C 149 ns.

Because of parity violation in the weak decay of the muon, a correlation exists between the muon spin and the direction of the high-energy decay electrons. Thus as the spin rotates relative to the momentum, the number of high-energy decay electrons is modulated by the frequency ω_a , as shown in Fig. 6. The E821 storage ring was constructed as a super-ferric magnet, meaning that the iron determined the shape of the magnetic field. Thus the magnetic field needed to be well below saturation and was chosen to be 1.45 T. The resulting ring had a central orbit radius of 7.112 m, and 24 detector stations were placed symmetrically around the inner radius of the storage ring. The detectors were made of Pb/SciFi electromagnetic calorimeters which measured the decay electron energy and time of arrival. The detector geometry and number were optimized to detect the high energy decay electrons, which carry the largest asymmetry, and thus information on the muon spin direction at the time of decay. In this design, many of the lower-energy electrons miss the detectors, reducing background and pileup.

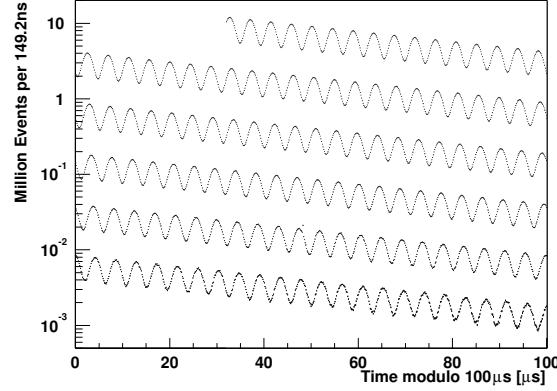


Figure 6: Distribution of electron counts versus time for the 3.6 billion muon decays. The data are wrapped around modulo $100 \mu\text{s}$ [8].

5 The Fermilab proposal: E989

The E989 collaboration at Fermilab plans to measure a_μ with an uncertainty of 1.6×10^{-10} (0.14 ppm), corresponding to a 0.10 ppm statistical error and roughly equal 0.07 ppm systematic uncertainties on ω_a and ω_p .

The proposal efficiently uses the unique properties of the Fermilab beam complex to produce the necessary flux of muons, which will be injected and stored in the (relocated) muon storage ring. To achieve a statistical uncertainty of 0.1 ppm, the total data set must contain more than 1.8×10^{11} detected positrons with energy greater than 1.8 GeV, and arrival time greater than $30 \mu\text{s}$ after injection into the storage ring. The plan uses 6 out of 20 of the 8-GeV Booster proton batches, each subdivided into four bunches of 10^{12} p/bunch. The proton bunches fill the muon storage ring at a repetition rate of 15 Hz, to be compared to the 4.4 Hz at BNL. The proton bunch hits a target, producing a 3.1 GeV/c pion beam that is directed along a greater than 1 km decay line. The resulting pure muon beam is injected into the storage ring. The muons will enter the ring through a new superconducting inflector magnet, which will replace the existing one, which is wound in such a manner that the coils intercept the beam on both ends of the magnet. The new inflector will result in a higher muon storage efficiency. Once entering the ring, an optimized pulse-forming network will energize the storage ring kicker to place the beam on a stable orbit. The pion flash (caused by pions entering the ring at injection) will be decreased by a factor of 20 from the BNL level, and the muon flux will be significantly increased because of the ability to take zero-degree muons. The stored muon-per-proton ratio will be increased by a factor of 5 to 10 over BNL.

The E821 muon storage will be relocated to Fermilab, in a new building with a stable floor and good temperature control, neither of which were available at Brookhaven.

The new experiment will require upgrades of detectors, electronics and data acquisition equipment to handle the much higher data volumes and slightly higher instantaneous rates. High-density segmented tungsten/scintillating-fibers [34] and crystals are considered as possible choice for the calorimeter. In-vacuum straw drift tubes have been developed to determine the stored muon distribution from decay positron tracks and to provide data for a greatly improved muon electric dipole moment measurement, which can be obtained in parallel [35]. A modern data acquisition system will be used to read out waveform digitizer data and store it so that both the traditional event mode and a new integrating mode of data analysis can be used in parallel. The systematic uncertainty on the precession frequency is expected to improve by a factor 3 thanks to the reduced pion contamination, the segmented detectors, and an improved storage ring kick of the muons onto orbit. The storage ring magnetic field will be shimmed to an even more impressive uniformity, and improvements in the field-measuring system will be implemented. The systematic error on the magnetic field is halved by better shimming, relocations of critical NMR probes, and other incremental changes.

In less than two years of running, the statistical goal of 4×10^{20} protons on target can be achieved for positive muons. A follow-up run using negative muons is possible, depending on future scientific motivation. Two additional physics results will be obtained from the same data: a new limit on the muon's electric dipole moment (up to 100 times better); and, a more stringent limit on possible CPT or Lorentz violation in muon spin precession. A technically driven schedule permits data taking to begin in 2016.

6 Prospects on a_μ

With the new experiments planned at Fermilab and J-PARC the uncertainty of the difference Δa_μ between the experimental and the theoretical value of a_μ will be dominated by the uncertainty of the hadronic cross sections at low energies, unless new experimental efforts at low energy are undertaken. The last column of Table 1 shows a future scenario based on realistic improvements in the $e^+e^- \rightarrow \text{hadrons}$ cross sections measurements. Such improvements could be obtained by reducing the uncertainties of the hadronic cross sections from 0.7% to 0.4% in the region below 1 GeV and from 6% to 2% in the region between 1 and 2 GeV as shown in Table 3.

In this scenario the overall uncertainty on Δa_μ could be reduced by a factor 2. In case the central value would remain the same, the statistical significance would become 7-8 standard deviations, as it can be seen in Fig. 7.

The effort needed to reduce the uncertainties of the $e^+e^- \rightarrow \text{hadrons}$ cross-sections according to Table 3 is challenging but possible, and certainly well motivated by the excellent opportunity the

	$\delta(\sigma)/\sigma$ present	$\delta a_\mu^{\text{HLO}}$ present	$\delta(\sigma)/\sigma$ prospect	$\delta a_\mu^{\text{HLO}}$ prospect
$\sqrt{s} < 1$ GeV	0.7%	3.3	0.4%	1.9
$1 < \sqrt{s} < 2$ GeV	6%	3.9	2%	1.3
$\sqrt{s} > 2$ GeV		1.2		1.2
total		5.3		2.6

Table 3: Overall uncertainty of the cross-section measurement required to get the reduction of uncertainty on a_μ^{HLO} in units 10^{-10} for three regions of \sqrt{s} (from Ref. [36]).

muon $g-2$ is providing us to unveil (or constrain) “new-physics” effects. A long-term program of hadronic cross section measurements at low energies is clearly warranted and fortunately it has been already started at VEPP-2000. In addition, recent theoretical activities focused on lattice calculation have already reached a mature stage and have real prospects to match the future experimental precision.

With the expected reduction of the error on a_μ^{HLO} , and the planned improved precision of the new $g-2$ experiments, the hadronic Light-by-Light contribution could become the main limitation for further progress on a_μ^{SM} . Although there isn’t a direct connection with data, $\gamma\gamma$ measurements performed at e^+e^- colliders will help us to constrain form factors [37]. Lattice calculation could help as well.

7 Conclusion

The measurements of the muon anomaly a_μ have been a important benchmark for the development of QED and the Standard Model. In the recent years, following the impressive accuracy (0.54 ppm) reached by the E821 experiment at BNL, a worldwide effort from different theoretical and experimental groups has significantly improved the SM prediction. At present there appears to be a 3σ difference between the experimental value and the SM prediction of a_μ . This discrepancy, which would fit well with SUSY expectations, is a valuable constraint in restricting physics beyond the Standard Model, guiding the interpretation of LHC results. In order to clarify the nature of the observed discrepancy between theory and experiment, and eventually firmly establish (or constrain) new physics effects, new direct measurements of the muon $g-2$ with a fourfold improvement in accuracy have been proposed at Fermilab by E989 and J-PARC. First results from E989 could be available around 2017/18.

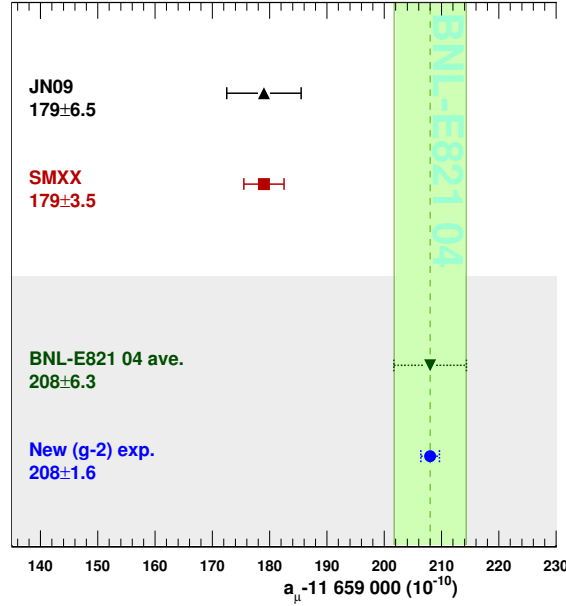


Figure 7: Comparison between a_μ^{SM} and a_μ^{EXP} . “JN09” is the current evaluation of a_μ^{SM} using Ref. [6]; “SMXX” is the same central value with a reduced error as expected by the improvement on the hadronic cross section measurement (see text); “BNL-E821 04 ave.” is the current experimental value of a_μ ; “New ($g-2$) exp.” is the same central value with a fourfold improved accuracy as planned by the future ($g-2$) experiments [9, 10].

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References

- [1] F. Jegerlehner, “The anomalous magnetic moment of the muon,” Berlin, Springer (2008) 426 p (Springer tracts in modern physics. 226)
- [2] D. Stöckinger, “Muon (g-2) and physics beyond the standard model,” In Roberts, Lee B., Marciano, William J. (eds.): Lepton dipole moments 393-438 (Advanced series on directions in high energy physics. 20)
- [3] H. N. Brown *et al.* [Muon g-2 Collaboration], Phys. Rev. Lett. **86** (2001) 2227
- [4] K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, J. Phys. G **38** (2011) 085003
- [5] J. Prades, hep-ph/0108192.
- [6] F. Jegerlehner and A. Nyffeler, Phys. Rept. **477** (2009) 1
- [7] M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C **71** (2011) 1515
- [8] G. W. Bennett *et al.* [Muon G-2 Collaboration], Phys. Rev. D **73** (2006) 072003
- [9] The New Muon (g - 2) Collaboration, R.M. Carey *et. al.*, see <http://lss.fnal.gov/archive/testproposal/0000/fermilab-proposal-0989.shtml>
- [10] J. Imazato, Nucl. Phys. Proc. Suppl. **129** (2004) 81.
- [11] S. Actis *et al.* [Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies Collaboration], Eur. Phys. J. C **66** (2010) 585
- [12] M. S. Chen and P. M. Zerwas, Phys. Rev. D **11** (1975) 58
- [13] S. Binner, J. H. Kuhn and K. Melnikov, Phys. Lett. B **459** (1999) 279
- [14] M. Benayoun, S. I. Eidelman, V. N. Ivanchenko and Z. K. Silagadze, Mod. Phys. Lett. A **14** (1999) 2605
- [15] W. Kluge, Nucl. Phys. Proc. Suppl. **181-182** (2008) 280
- [16] V. P. Druzhinin, S. I. Eidelman, S. I. Serednyakov and E. P. Solodov, Rev. Mod. Phys. **83**, (2011) 1545
- [17] J. Prades, E. de Rafael and A. Vainshtein, (Advanced series on directions in high energy physics. 20)

- [18] X. Feng, K. Jansen, M. Petschlies and D. B. Renner, arXiv:1103.4818 [hep-lat]
- [19] F. Jegerlehner and R. Szafron, Eur. Phys. J. C **71** (2011) 1632
- [20] M. Benayoun, P. David, L. Del Buono and F. Jegerlehner, Eur. Phys. J. C **72** (2012) 1848
- [21] J. Z. Bai *et al.* [BES Collaboration], Phys. Rev. Lett. **88** (2002) 101802
- [22] R. R. Akhmetshin *et al.* [CMD-2 Collaboration], Phys. Lett. B **648** (2007) 28
- [23] R. R. Akhmetshin *et al.* [CMD-2 Collaboration] JETP Lett. **84** (2006) 413 [Pisma Zh. Eksp. Teor. Fiz. **84** (2006) 491]
- [24] R. R. Akhmetshin *et al.* [CMD-2 Collaboration], Phys. Lett. B **578** (2004) 285
- [25] M. N. Achasov *et al.*, J. Exp. Theor. Phys. **103** (2006) 380
- [26] F. Ambrosino *et al.* [KLOE Collaboration], Phys. Lett. B **700** (2011) 102
- [27] F. Ambrosino *et al.* [KLOE Collaboration], Phys. Lett. B **670** (2009) 285
- [28] A. Aloisio *et al.* [KLOE Collaboration], Phys. Lett. B **606** (2005) 12
- [29] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **103** (2009) 231801
- [30] S. R. Amendolia *et al.* [NA7 Collaboration], Nucl. Phys. B **277** (1986) 168
- [31] G. Venanzoni for the KLOE/KLOE-2 Collaborations, proceedings of EPS-HEP 2011 Conference, Grenoble
- [32] E. P. Solodov, presentation at the International Workshop on e+e- collisions from Phi to Psi (PHIPSI11), September 19-22 2011, Novosibirsk; S. I. Serednyakov presentation at the International Workshop on e+e- collisions from Phi to Psi (PHIPSI11), September 19-22 2011, Novosibirsk
- [33] D. Babusci *et al.*, arXiv:1007.5219 [hep-ex].
- [34] R. McNabb *et al.*, Nucl. Instrum. Meth. A **602** (2009) 396
- [35] G. W. Bennett *et al.* [Muon (g-2) Collaboration], Phys. Rev. D **80** (2009) 052008
- [36] F. Jegerlehner, Nucl. Phys. Proc. Suppl. **181-182** (2008) 26.
- [37] D. Babusci *et al.*, arXiv:1109.2461 [hep-ph]